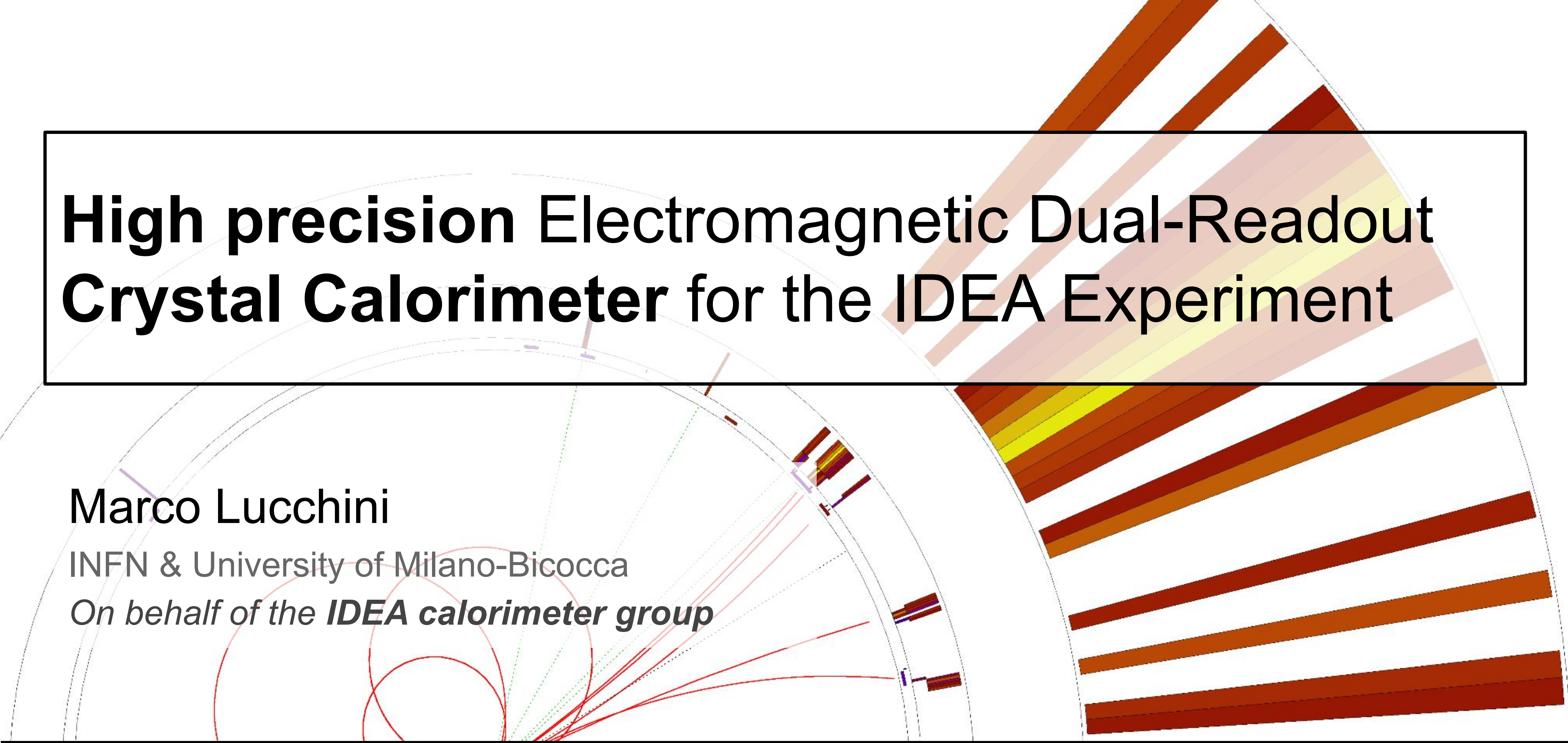
High precision Electromagnetic Dual-Readout **Crystal Calorimeter** for the IDEA Experiment



Marco Lucchini

INFN & University of Milano-Bicocca

*On behalf of the **IDEA calorimeter group***

FCC-France & Italy Workshop on Higgs,Top, EW, HF Physics in Lyon

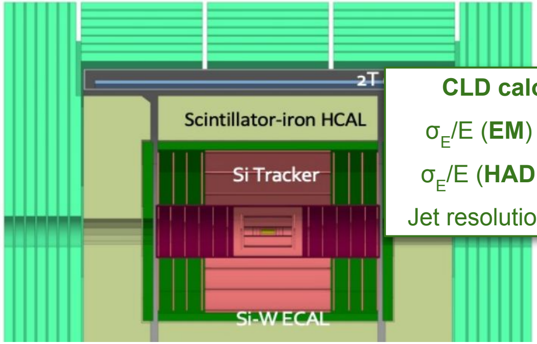
21-23 November 2022

Baseline detector concepts for future e^+e^- colliders

General purpose detector concepts at future e^+e^- colliders:

- **CLD**: Exploiting high granularity for particle flow algorithms (combining tracker and calorimeter exploiting topological information)
- **IDEA**: Exploiting the dual-readout approach (correct for EM fluctuations in hadronic shower developments)
- **Noble Liquid:** large(r) sampling fraction and light yield combined with reasonable granularity

- **EM energy resolution is far from that of state-of-the-art homogeneous crystal calorimeters (1-3%/√E)**

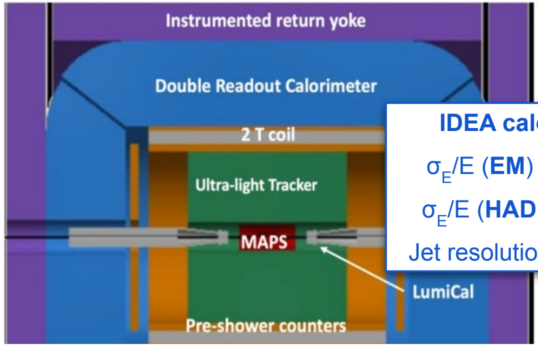


CLD calorimeter

σ_E/E (**EM**) ~16%/√E

σ_E/E (**HAD**) ~45%/√E

Jet resolution ~ 30%/√E

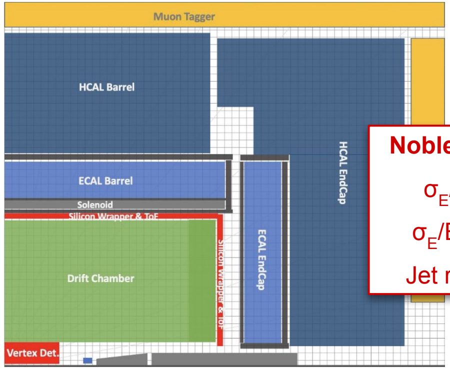


IDEA calorimeter

σ_E/E (**EM**) ~13%/√E

σ_E/E (**HAD**) ~31%/√E

Jet resolution ~ 30%/√E



Noble liquid calorimeter

σ_E/E (**EM**) ~8%/√E

σ_E/E (**HAD**) ~37%/√E

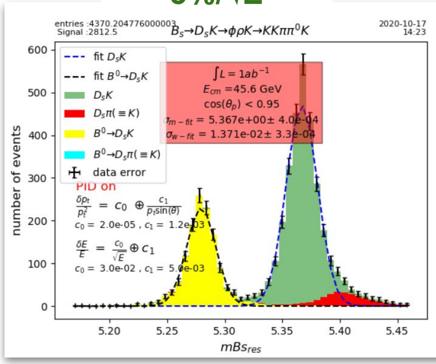
Jet resolution ~ ?%/√E

Potential for high EM energy resolution

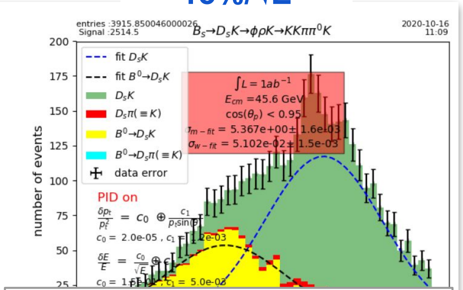
A calorimeter with **3%/√E** EM energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at e^+e^- colliders

- **CP violation studies** with B_s decay to final states with low energy photons
- **Clustering of π^0's photons** to improve performance of jet clustering algorithms
- **Improve the resolution of the recoil mass signal from Z→ee decays** to ~80% of that from Z→ μμ decays (recovering Brem photons)

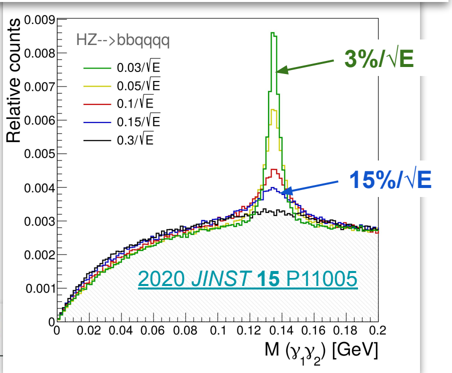
3%/√E



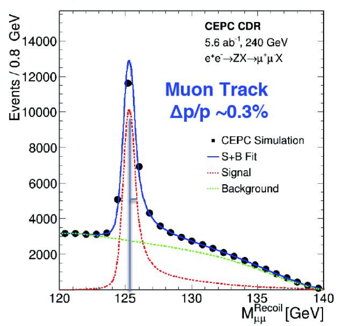
15%/√E



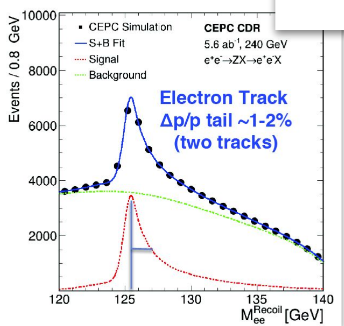
R.Aleksan et al., *Study of CP violation in $B^\pm$ decays to D0(D0)$K^\pm$ at FCCee*, arXiv:2107.05311



Z→$\mu^+\mu^-$ Recoil



Z→e^+e^- Recoil



Example from CEPC CDR

Technological progress in the field of scintillators and photodetectors has **enabled** the design of **a cost-effective and highly performant calorimeter**

Excellent energy resolution to photons and neutral hadrons
(~3%/√E and ~30%/√E respectively)

Separate readout of scintillation and Cherenkov light
(to exploit dual-readout technique for hadron resolution and linearity)

Longitudinal and transverse segmentation
(to provide more handles for particle flow algorithms)

Energy resolution at the level of 4-3% for 50-100 GeV jets

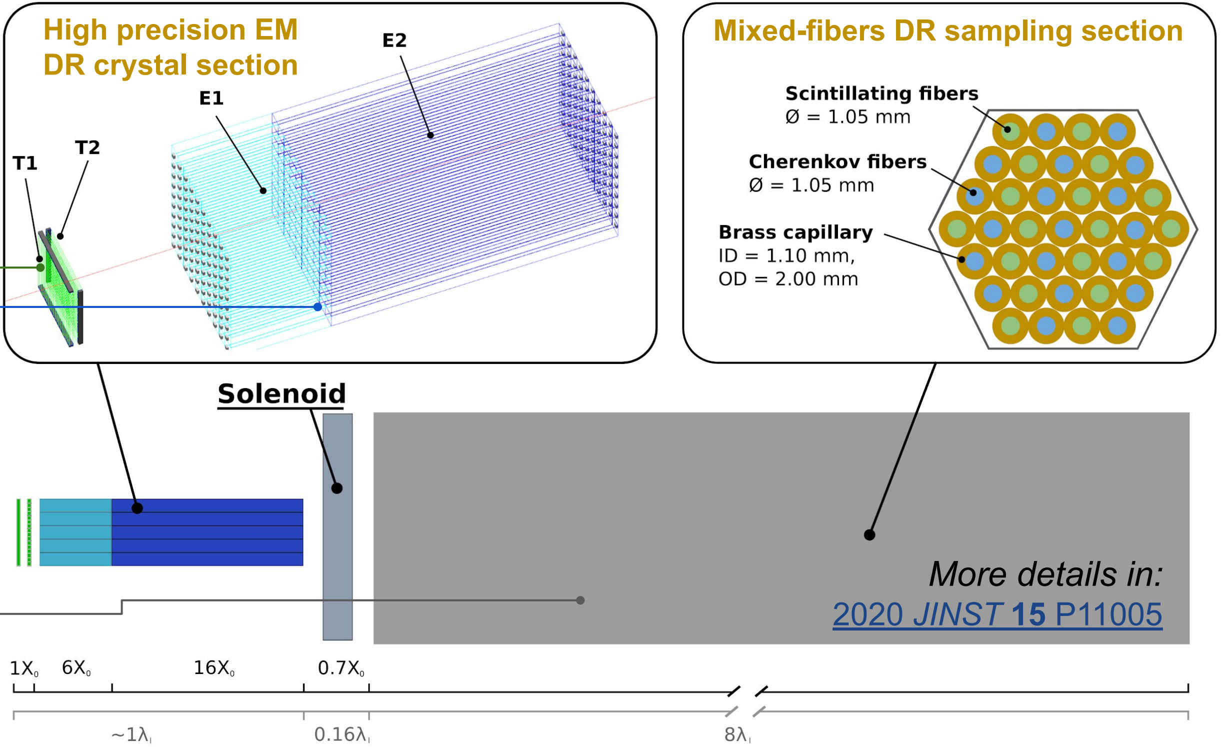
Precise time tagging for both MIPs and EM showers
(time resolution better than 30 ps)

"Maximum information" calorimetry
(**6D**: x,y,z,t,E,C/S)

Conceptual layout

- **Transverse and longitudinal segmentation** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals ($\sim 1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment ($\sim 6X_0$)
  - Rear segment ($\sim 16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - $\sim 0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
  - Scintillating and “clear” PMMA fibers (for Cherenkov signal) inserted inside brass capillaries

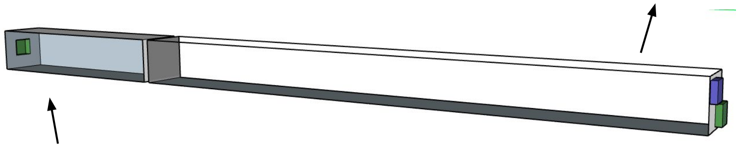


More details in: [2020 *JINST* **15** P11005]

Implementation of dual-readout in the crystal section

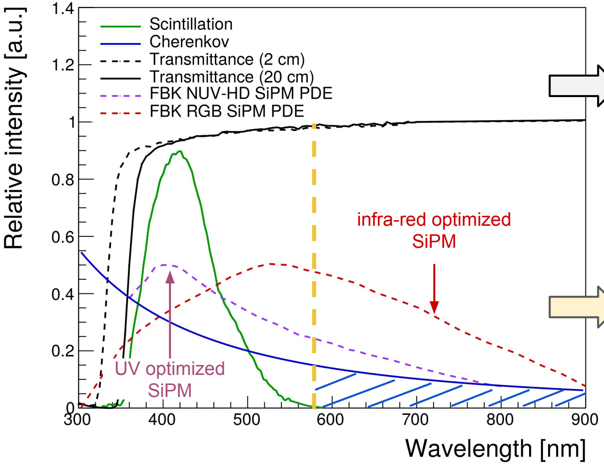
- Simultaneous readout of scintillation and Cherenkov light from the rear segment with dedicated SiPMs+wavelength filters

Rear crystal ECAL segment:
Two 4x4 mm² SiPMs with optical filters optimized for scintillation and cherenkov detection resp.



Front crystal ECAL segment:
Single 5x5 mm² SiPM per crystal optimized for scintillation light detection

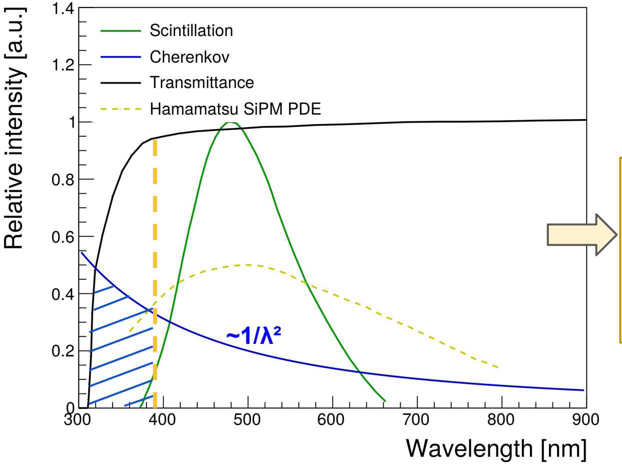
PWO



Estimated:
- >2000 phe/GeV for scintillation photons
- >100 phe/GeV for Cherenkov photons

Cherenkov photons above scintillation peak are much less affected by self-absorption

BGO / BSO



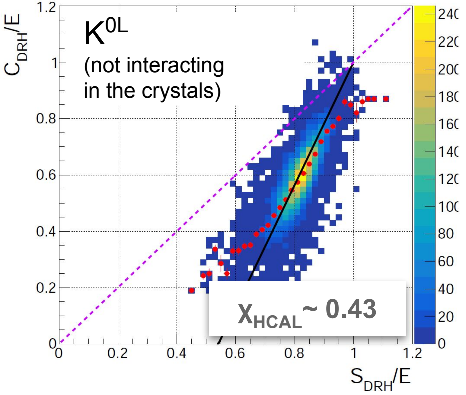
BGO/BSO have larger stokes shift, i.e. a wider range of transparency for 'UV Cherenkov'

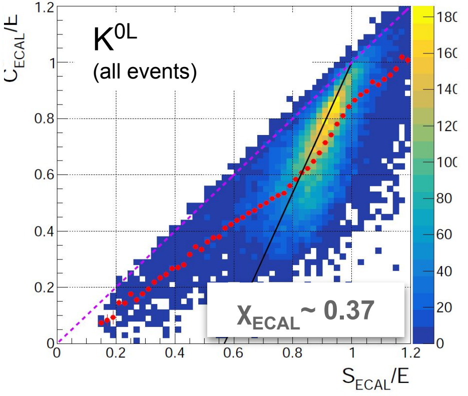
The **dual-readout method** in a hybrid calorimeter

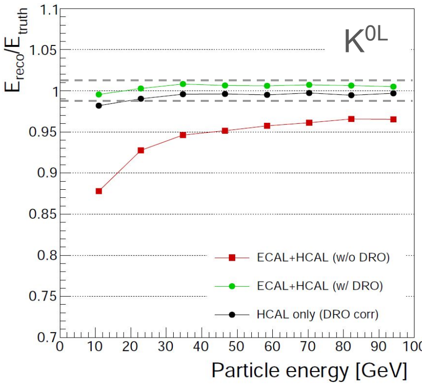
- Apply the DR correction on the energy deposits in the crystal and fiber segments first and then s um up the corrected energy from both segments

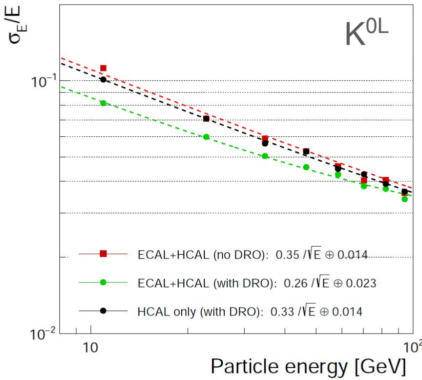
$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}}$$
$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1 - \chi_{ECAL}}$$
$$E_{total} = E_{HCAL} + E_{ECAL}$$

- **Dual-readout method confirms its applicability in a hybrid calorimeter**
  - Response linearity to hadrons restored within ±1%
  - Hadron energy resolution comparable to that of the fiber-only IDEA calorimeter



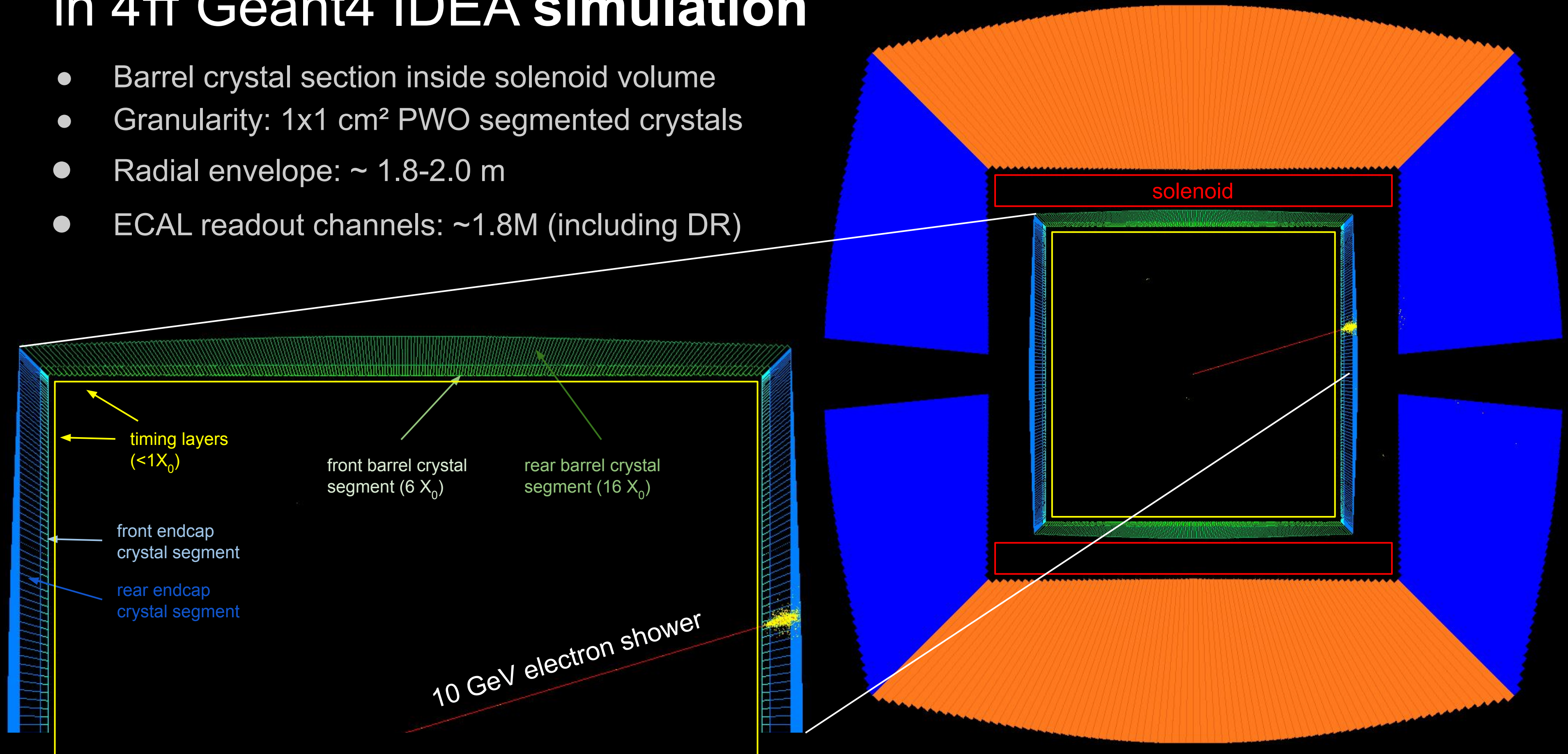






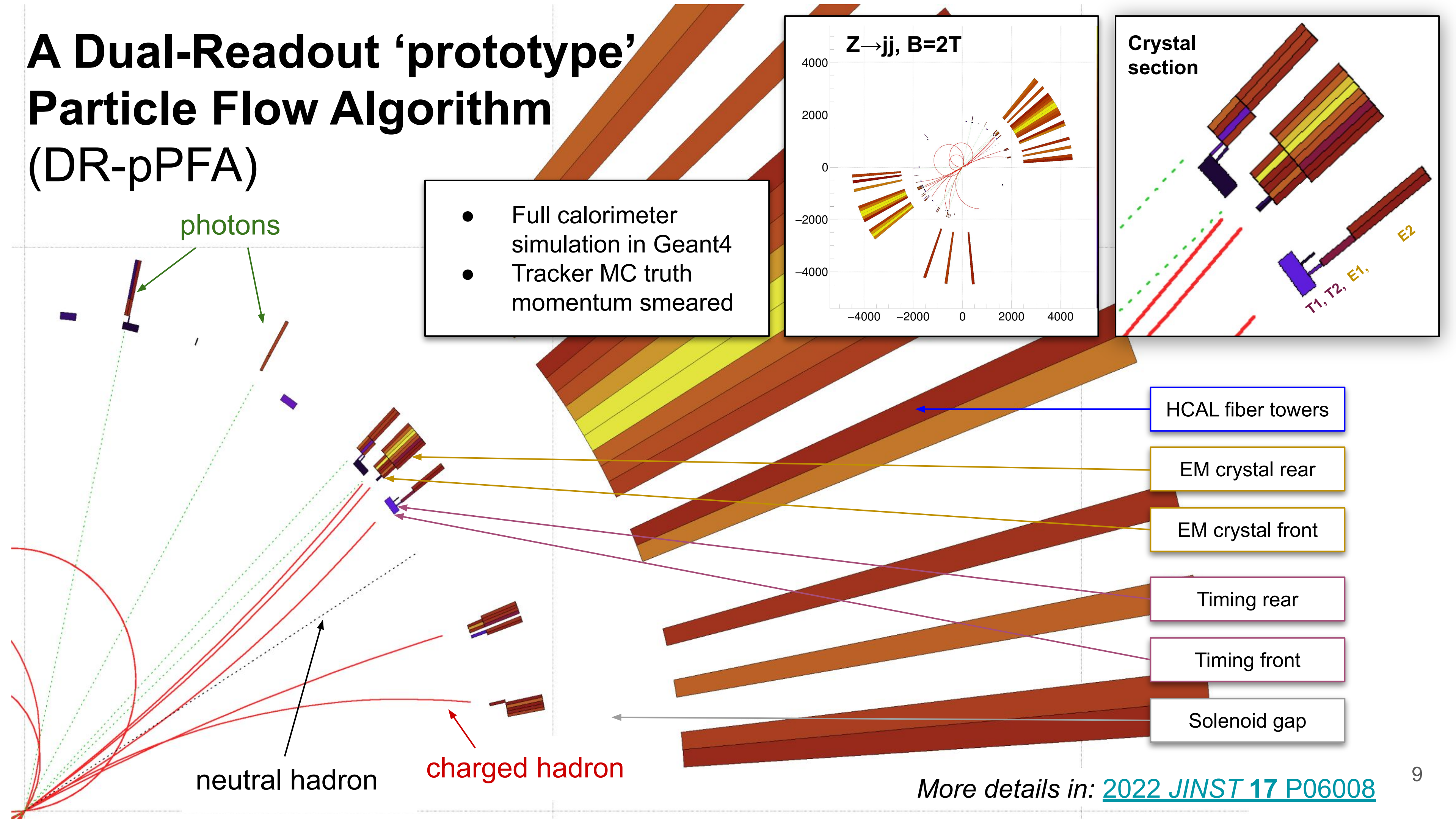
Integration of crystal EM calorimeter in 4π Geant4 IDEA **simulation**

- Barrel crystal section inside solenoid volume
- Granularity: 1x1 cm² PWO segmented crystals
- Radial envelope: ~ 1.8-2.0 m
- ECAL readout channels: ~1.8M (including DR)



A Dual-Readout 'prototype' Particle Flow Algorithm
(DR-pPFA)

- Full calorimeter simulation in Geant4
- Tracker MC truth momentum smeared



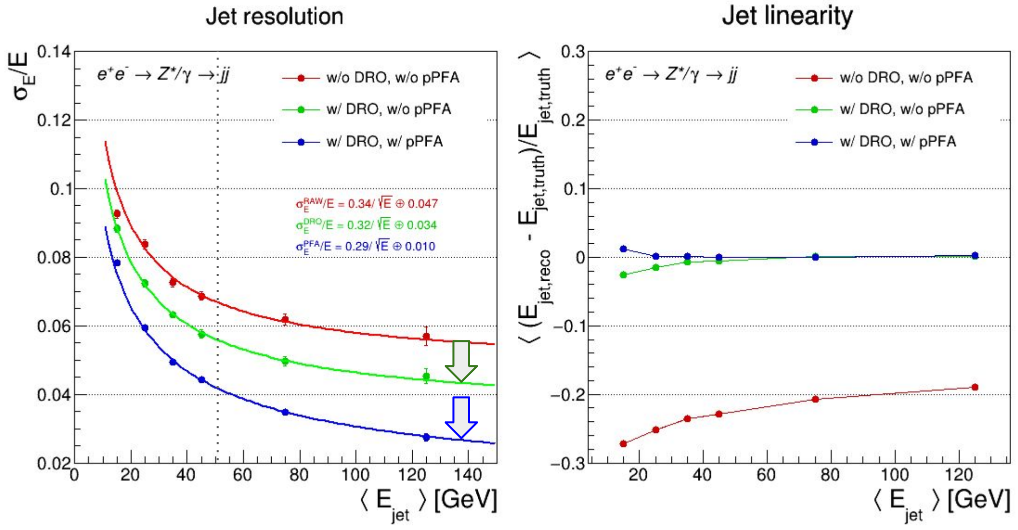
More details in: [2022 *JINST* **17** P06008]

Jet resolution: with and without DR-pPFA

More details in:
[2022 *JINST* **17** P06008]

Jet energy resolution and linearity as a function of jet energy in off-shell $e^+e^- \to Z^* \to jj$ events (at different center-of-mass energies):

- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA

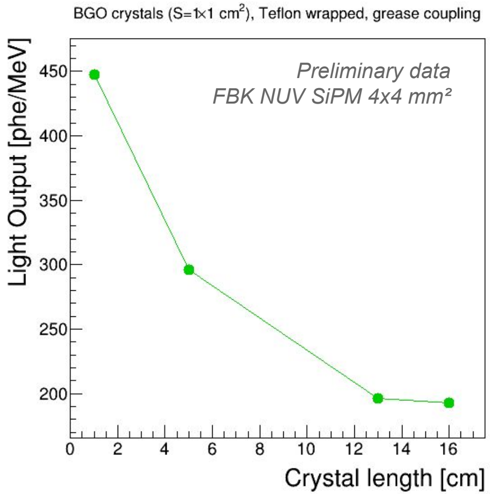


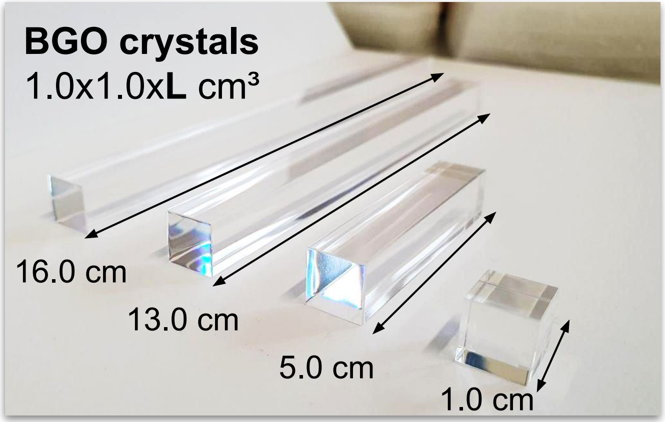
Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

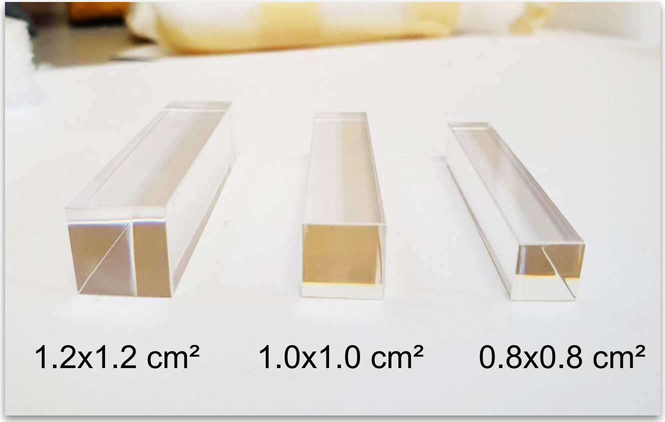
Ongoing effort to repeat the study with full simulation including tracker and with edm4hep data format: see talk from A.D'Onofrio in the afternoon

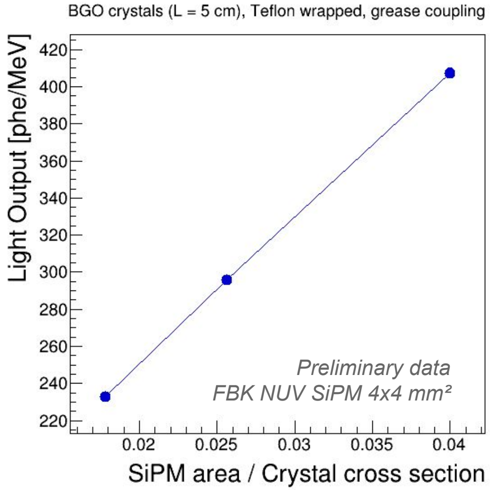
Ongoing R&D: calorimeter cell optimization

- Optimization of crystal cross section (granularity) and longitudinal segmentation
- Evaluation of light output for different crystal and SiPM geometries
- First experimental results available to validate expectations from Geant4 ray-tracing simulation









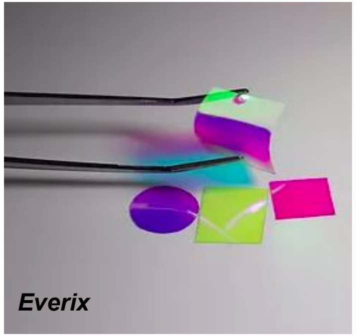
Ongoing R&D: dual-readout challenge

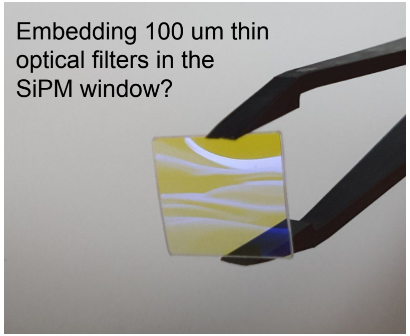
Multi-signal readout challenges:

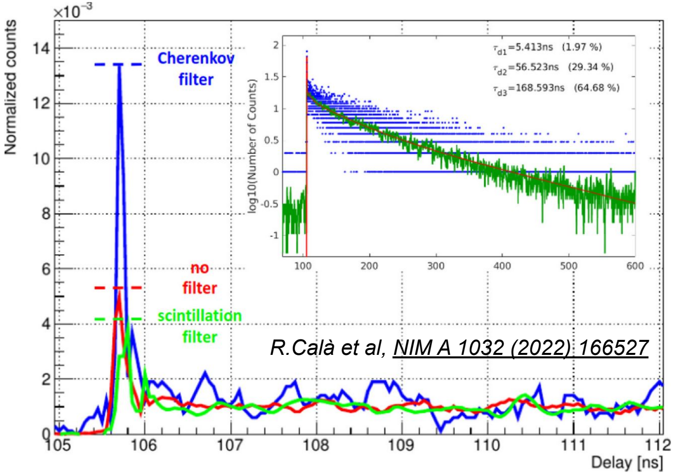
- Challenging dynamic range and photon sensitivity with SiPMs
- Reasonable **scintillation** and **cherenkov** light yields (>2000 phe/GeV and >100 phe/GeV resp.)
- **Good separation of scintillation and cherenkov signals** (e.g. based on thin wavelength filters)

Exploring crystal candidates with high Cherenkov yield and density (PWO, BGO, BSO)

- See also optimization study of BGSO crystals *R.Calà et al, [NIM A 1032 (2022) 166527](https://doi.org/10.1016/j.nima.2022.166527)*







Summary

- EM energy resolution at the 1-3%/√E level can **expand the physics potential of e^+e^- collider experiments** providing enhanced sensitivity to low energy photons

- A **dual-readout hybrid calorimeter** (homogeneous crystals + fibers in brass tubes) **can meet the requirements of EM, HAD and jet energy resolution** (through the development of dedicated dual-readout particle flow algorithms)

- **Growing national and international efforts** (INFN MiB&Napoli, Calvision in US, Lab27 at CERN) to address **R&D challenges** and development of simulation tools to optimize a cost-effective calorimeter design

Additional material

Outlook and next steps

- Hardware / prototyping:
  - Identification of best crystal and SiPM candidates (+ wavelength filters)
  - Optimization of calorimeter cell design (geometry)
  - Demonstration of S and C light outputs
  - Proof-of-concept of dual-readout functionality with cosmic ray bench
  - Towards EM calorimeter module prototype for beam test

- Software / simulation
  - Migration of crystal calorimeter simulation in the latest IDEA Geant4 simulation with the edm4hep data format
  - Development of a DD4HEP version of the crystal geometry
  - Continue development of dedicated **DR-PFlow algorithms** with full detector simulation
  - Explore physics benchmarks benefiting from high energy resolution for photons

Energy resolution for **EM particles**

- Contributions to energy resolution:
  - Shower fluctuations
    - Longitudinal leakage (0.5% constant)
    - Tracker material budget (~1% stoch.)
    - Services for front layers readout (~1% stoch.)
  - Photostatistics
    - Tunable parameter depending on:
      - SiPM choice (PDE, active area)
      - Crystal choice (light yield, emission wavelength)
  - Noise
    - Negligible with SiPMs
      - High gain devices (~10^5)
        → negligible noise from electronics
      - Small dark count rate within signal integration time window (e.g. <1 MHz/mm² → < 5 phe of noise for 200 mm² SiPM and 100 ns signal integration gate)

$$\frac{\sigma_E}{E} = \frac{3\%}{\sqrt{E}} \oplus \frac{0.2\%}{E} \oplus 0.5\%$$

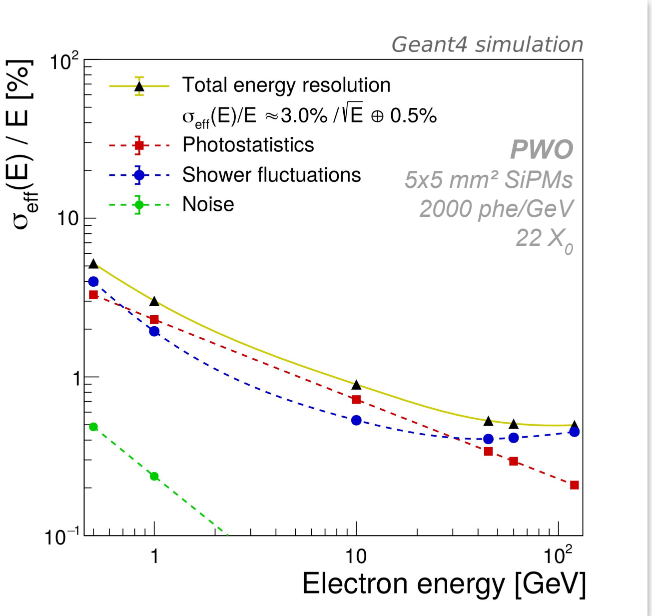


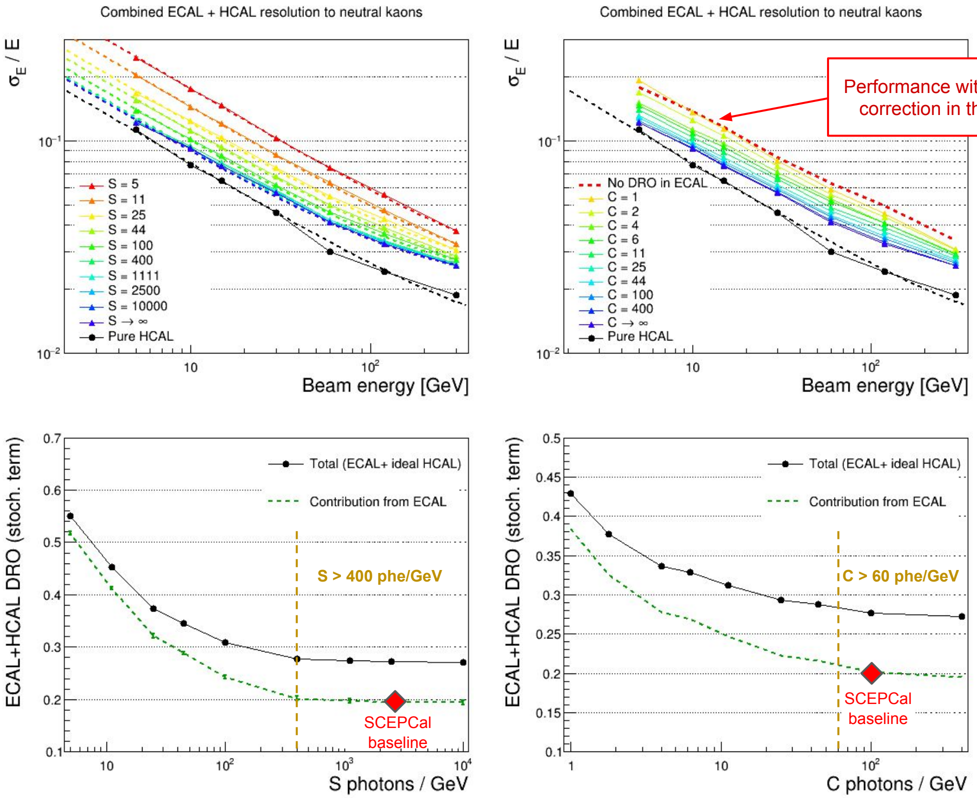
Photo-statistic requirements for S and C

- A poor S (scintillation signal) impacts the hadron (and EM) resolution stochastic terms:
  - S > 400 phe/GeV

- A poor C (Cherenkov signal) impacts the C/S and thus the precision of the event-by-event DRO correction
  - C > 60 phe/GeV

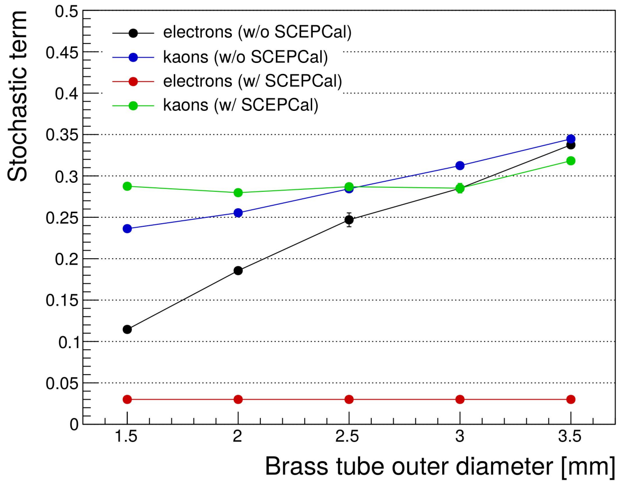
- **SCEPCal layout choices** (granularity and SiPM size) **provide sufficient light collection efficiency**
  - Need experimental validation with lab and beam tests

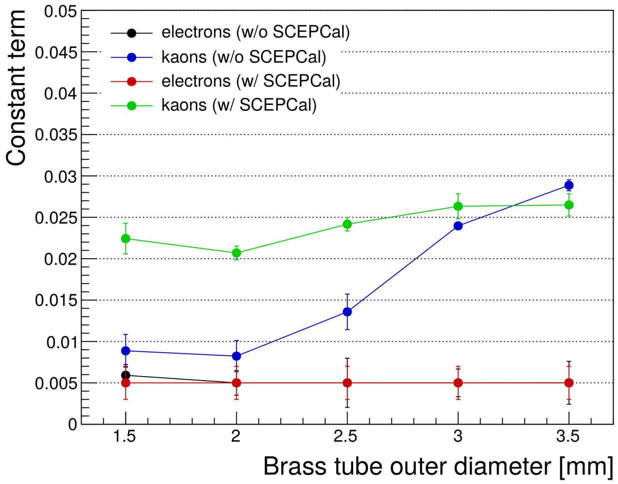
Smearing according to Poisson statistics

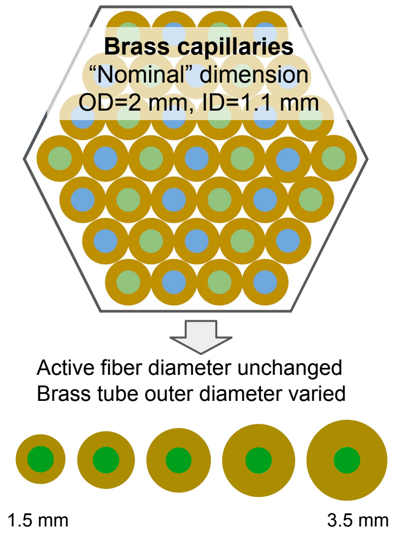


Calorimeter **cost/performance optimization**

- **Integration of crystals section for EM particles with IDEA calorimeter offers room for overall detector cost optimization**
  - Reduce sampling fraction and readout granularity in the hadronic segment (fibers-absorber sampling calorimeter) with limited impact on hadron resolution
    [e.g. increase of the brass tube outer diameter (OD) to 3-3.5 mm]
  - Relative channel reduction and cost decrease approximately with ~1/OD^2





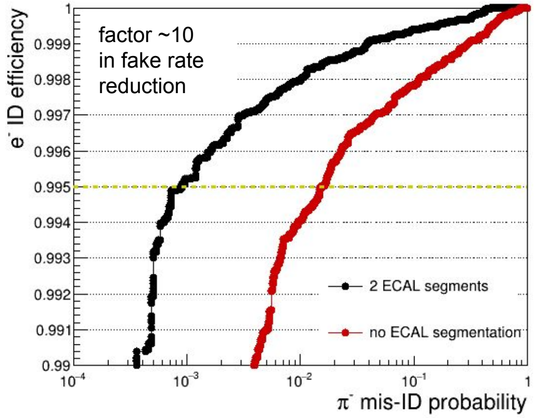


PID: crystal longitudinal **segmentation matters**

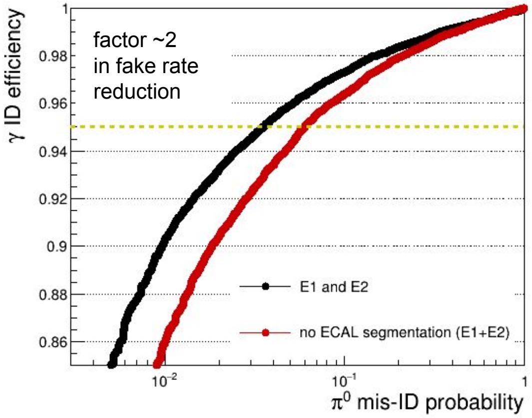
- Tangible improvements in particle ID from the longitudinal ECAL segmentation, i.e. **two crystal segments** (front and rear) instead of a single crystal cell

Single particle gun events with uniform energy distribution in the range 1-100 GeV, 100k events for each type of particle

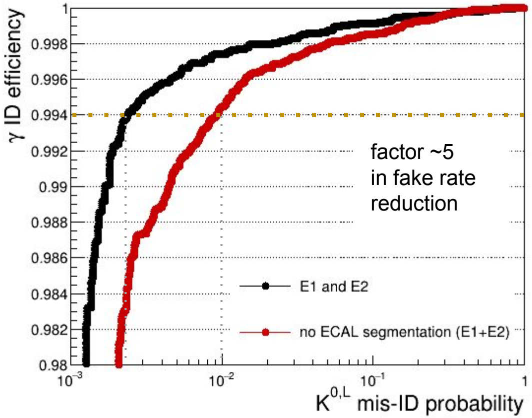
$\pi^{\pm} / e^{\pm}$



π^{0} / γ



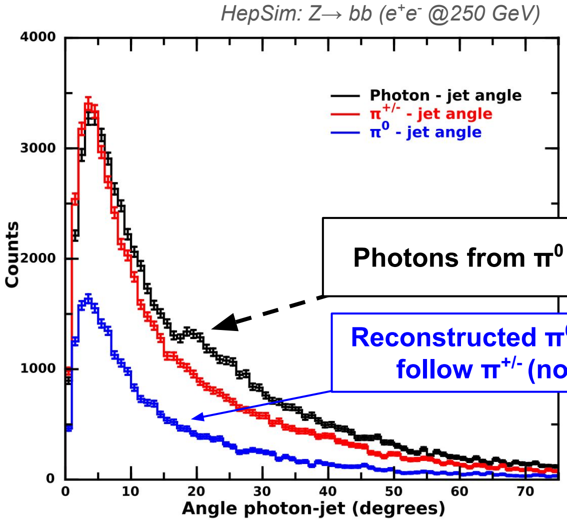
K^{0L} / γ

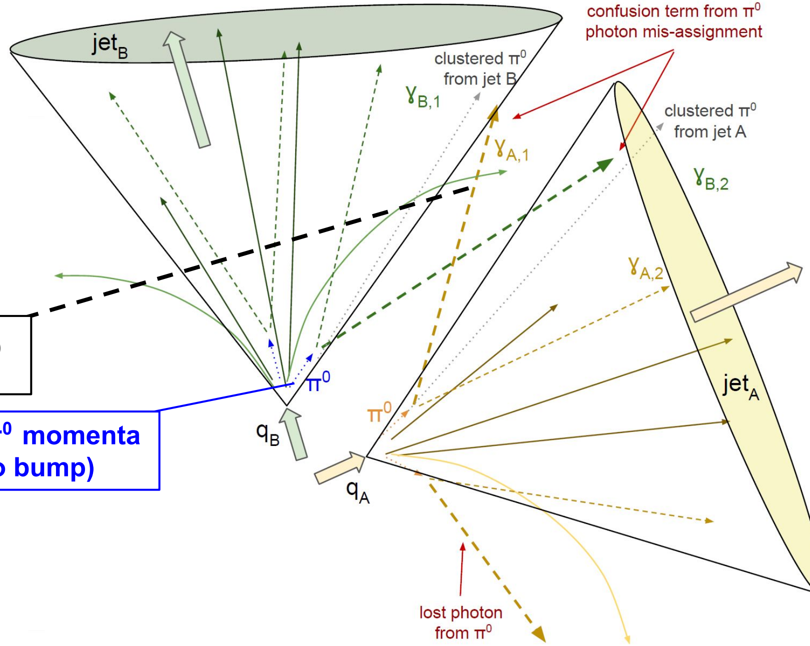


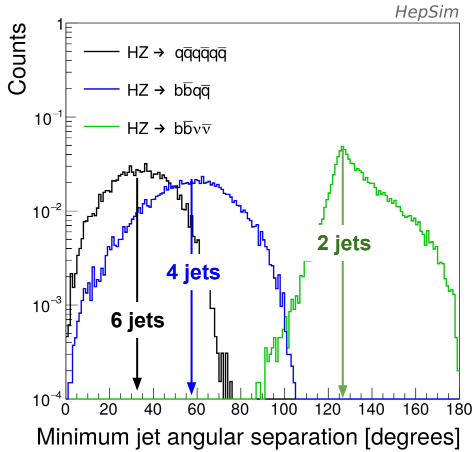
Impact of high EM resolution on reconstruction and physics

High photon resolution potential for PFA

- **Many photons from π^0 decay** are emitted **at a ~20-35° angle** wrt to the jet momentum and can get scrambled across neighboring jets
- Effect **particularly pronounced in 4 and 6 jets topologies**

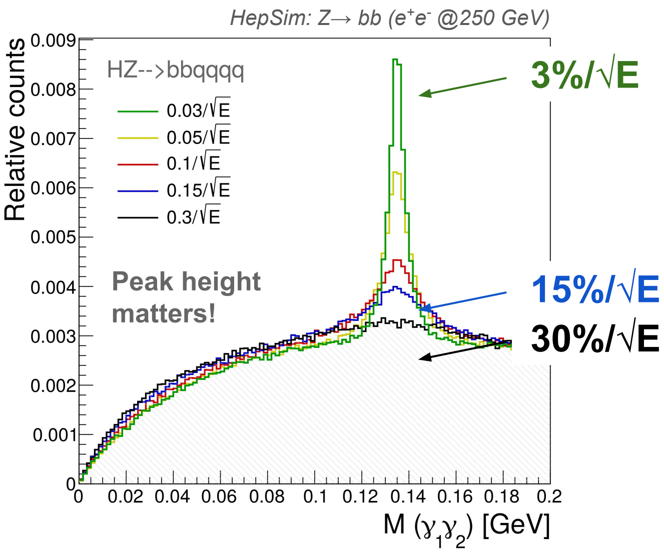


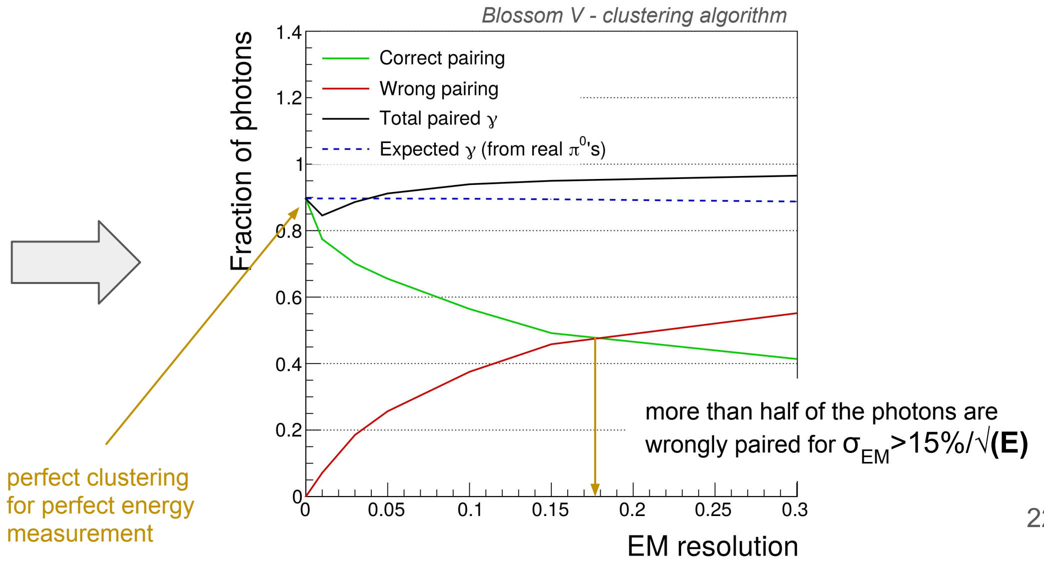




A graph-based algorithm for **π^0 clustering**

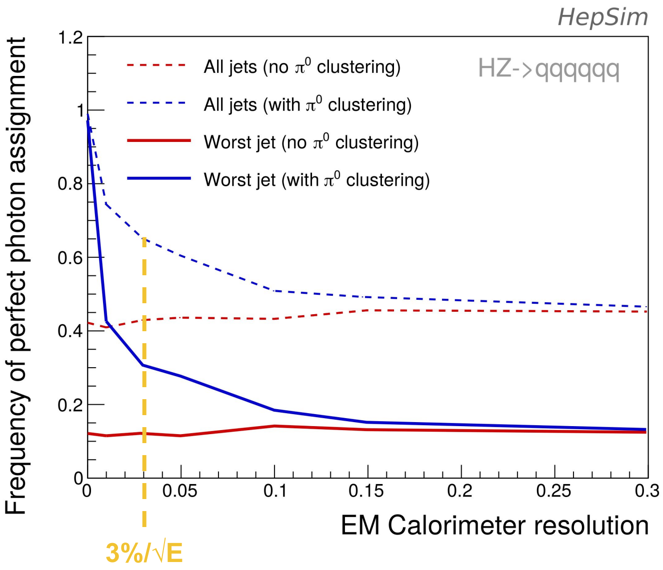
- **A high EM resolution enables efficient clustering of photons from π^0's**
  - Large fraction of π^0 photons correctly clustered with good σ_{EM}
    → **~90% for ~3%/√(E)** vs **50% for ~30%/√(E)**
  - Large fraction of "**fake π^0's**" reconstructed with poor σ_{EM}
    → ~50% for ~30%/√(E) vs 10% with ~3%/√(E)

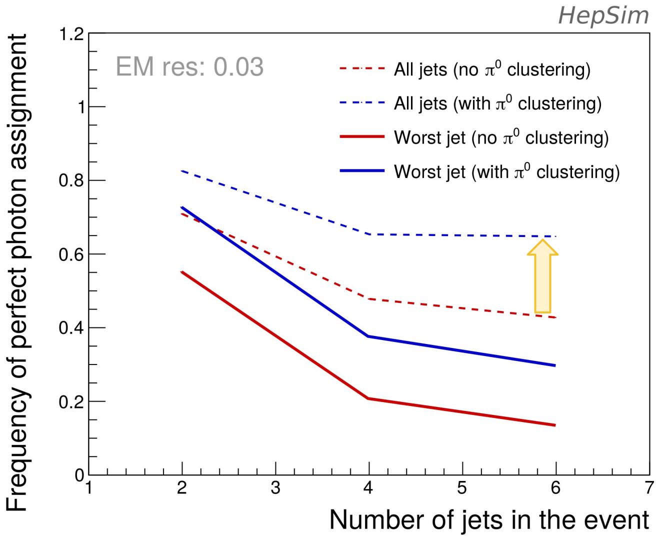




Improvements in photon-to-jet correct assignment

- **High e.m. resolution enables** photons **clustering into π⁰'s** by reducing their angular spread with respect to the corresponding jet momentum
- **Improvements in the fraction of photons correctly clustered to a jet** sizable only for e.m. resolutions of ~3%/√(E)

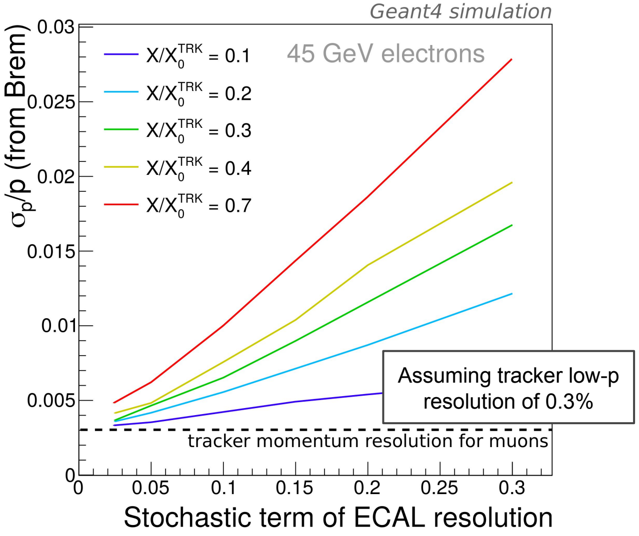




More details in:
https://doi.org/10.1088/1748-0221/15/11/P11005

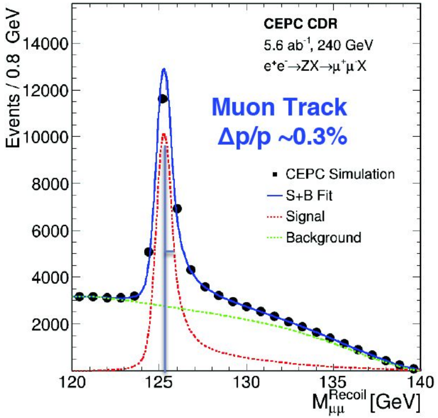
Recovery of Bremsstrahlung photons

- Reconstruction of the Higgs boson mass and width from the recoil mass of the Z boson is a key tool at e^+e^- colliders
- Potential to **improve the resolution of the recoil mass signal from Z→ee decays** to about 80% of that from Z→ μμ decays [with Brem photon recovery at EM resolution of 3%/√E]

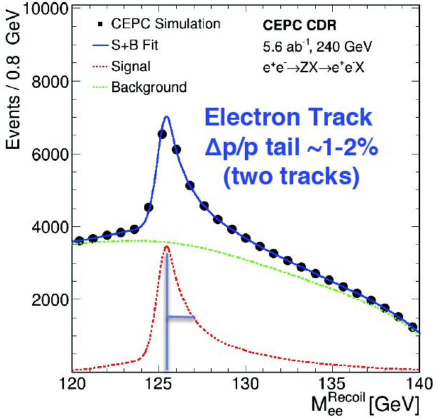


Example from CEPC CDR

Z→$\mu^+\mu^-$ Recoil



Z→e^+e^- Recoil



~80% of resolution recovery with 3%/√(E)

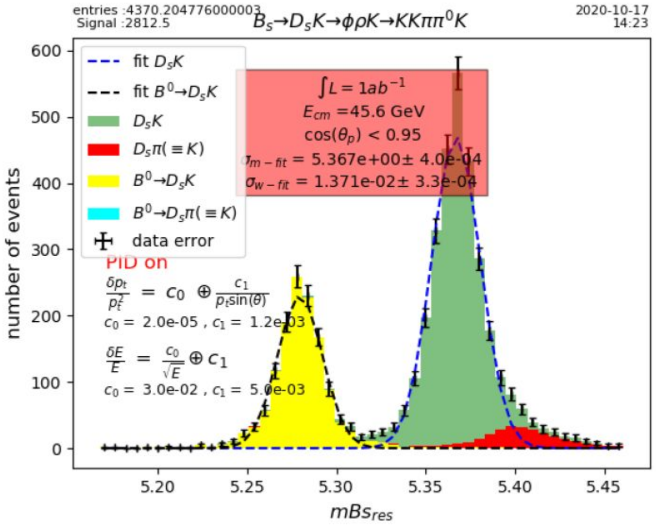
Studies of CP violation and EW physics at e^+e^- colliders

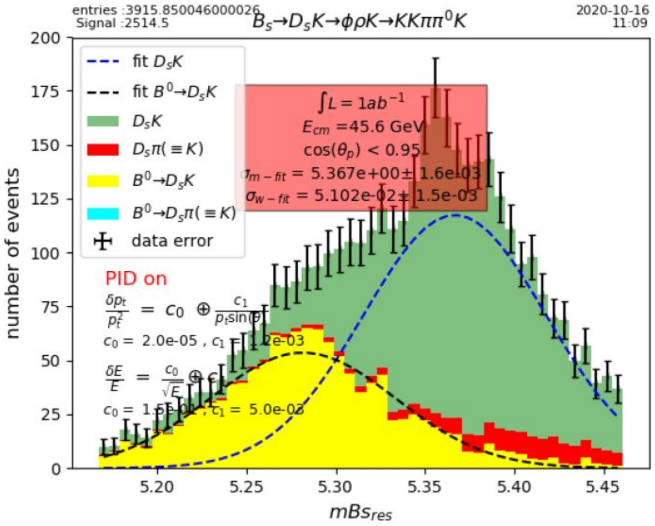
$\overline{B}_s$ decay Mode	Decay Mode	Final State	Number of $\overline{B}_s$ decays
$D_s^+ K^-$	$D_s^+ \to \phi\pi$	$K^+K^-\pi^+K^-$	$\sim 5.2\ 10^5$
$D_s^+ K^-$	$D_s^+ \to \phi\rho$	$K^+K^-\pi^+K^-\pi^0$	$\sim 9.8\ 10^5$

EM energy resolution at 3%/√E is required to study B_s decay final states with multiple neutrals

$$\frac{\delta E}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005$$

$$\frac{\delta E}{E} = \frac{0.15}{\sqrt{E}} \oplus 0.005$$

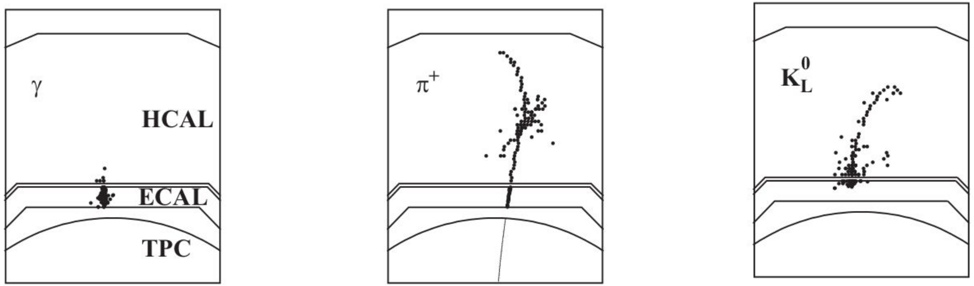




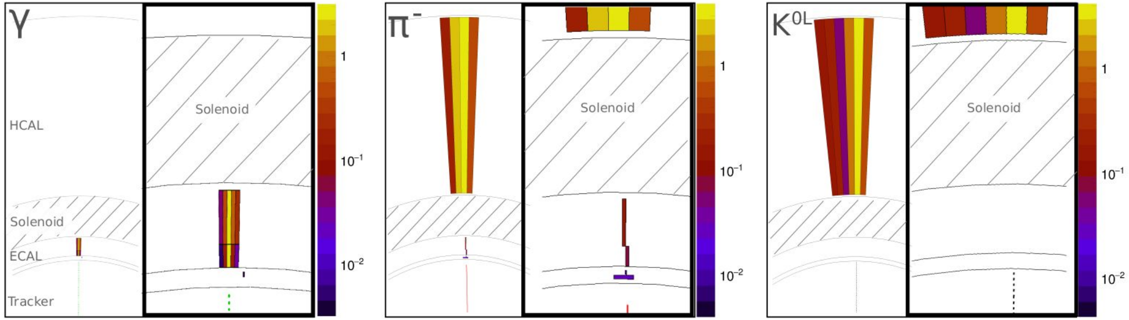
See **R. Aleksan's** talk @ [4th FCC Physics and Experiments Workshop]

More on DR-pPFA

Single particle identification through 'hits-topology'



Typical PFA with Si-W high granularity calorimeter



DR-pPFA with high resolution DRO calorimeter

A moderate longitudinal segmentation, fine transverse granularity and the highest energy resolution for single particle identification

A different basis for a DR-oriented PF algorithm

- Could the **better energy linearity and resolution** offset the coarser longitudinal segmentation?

	High granularity Si/W ECAL and scintillator based HCAL	Fiber-based dual-readout calorimeter	Hybrid crystal and dual-readout calorimeter
N. of longitudinal layers	> 40	1	5
ECAL cell cross-section HCAL cell cross-section	25–100 mm^2 100–900 mm^2	2–144 mm^2	100 mm^2 400–2500 mm^2
EM energy resolution HAD energy resolution	$15-25\%/\sqrt{E}$ $45-55\%/\sqrt{E}$	$10-15\%/\sqrt{E}$ $25-30\%/\sqrt{E}$	$\approx 3\%/\sqrt{E}$ $\approx 25-30\%/\sqrt{E}$

Moderate longitudinal segmentation (helpful to identify and measure the π^0 component of jets)

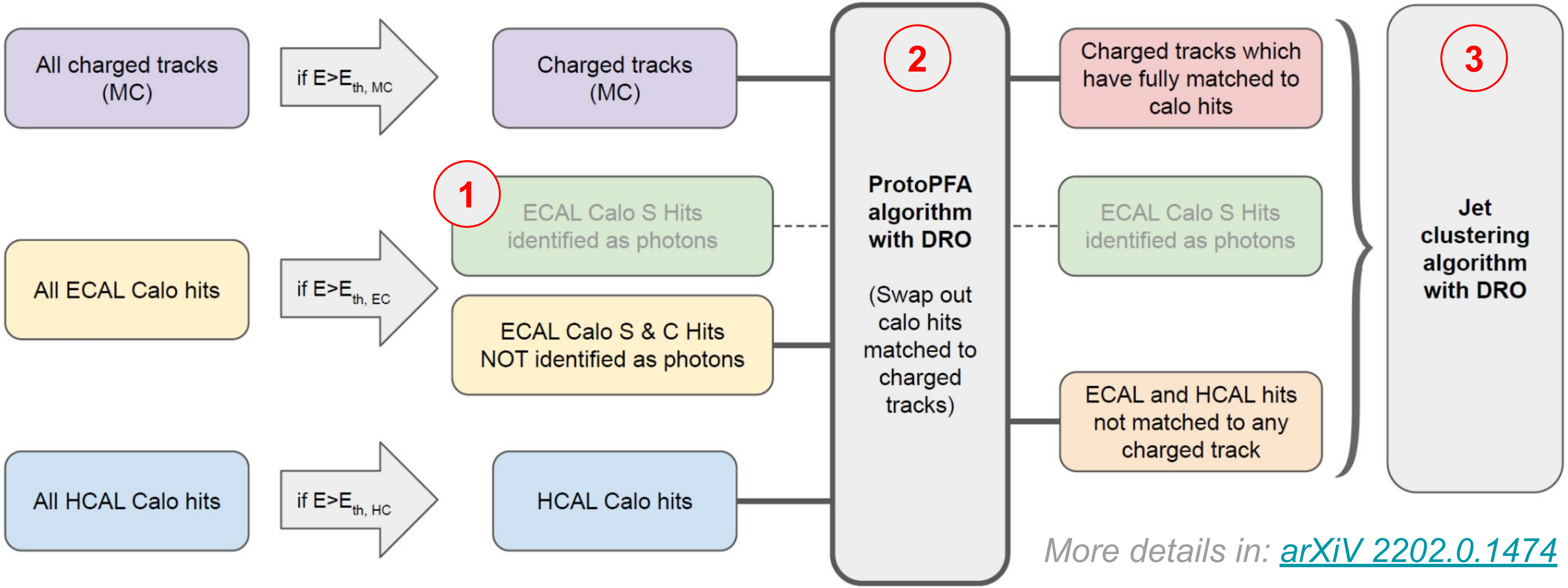
Highest energy resolution and linearity

Highest longitudinal segmentation

Highest transverse segmentation: full potential (e.g. using neural networks) yet unexplored

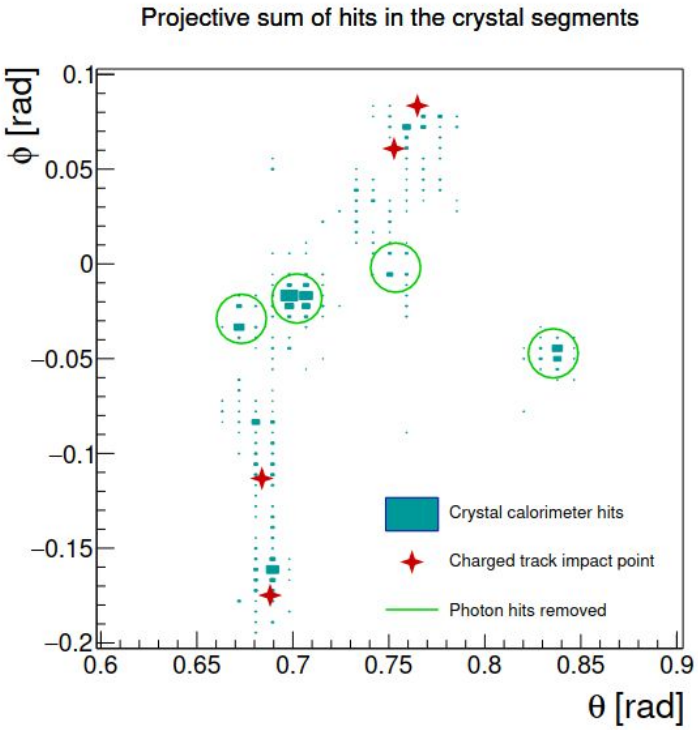
Dual-Readout Particle Flow Algorithm for jet reconstruction

- Maximally exploit the information from the **crystal ECAL** for classification of EM clusters and use it **as a linchpin** to provide stronger criteria in matching to the tracking and hadron calorimeter hits
- Exploit the **high resolution and linear response** of the hybrid **dual-readout** calorimeter to improve precision of the track-calo hits matching in a particle flow approach



More details in: arXiV 2202.0.1474

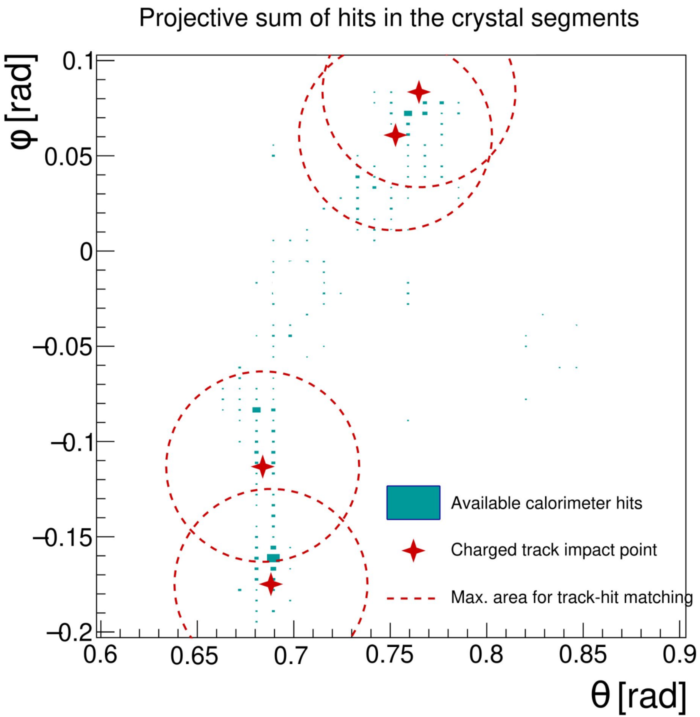
Step 1) Identification of photon hits



- Calorimeter hits **in the crystal segments** are analyzed
- Neutral seeds are identified as hits above a certain threshold and which have no charged track pointing to them
- Hits within a cone of R<0.013 are clustered around the "**photon seeds**"
- Such **"photon hits"** do not take part to step 2 (association of calorimeter hits with charged tracks)

**longitudinal segmentation (EM crystal section) is crucial for this step*

Step 2) Association of calorimeter hits to charged tracks



- Calorimeter hits **in both calorimeter segments** are parsed
- Hits are associated to tracks based on their distance from a certain track
- **Successful match**: if the sum of the energy of hits associated to a track is within ±1σ from the expected track signal the calorimeter hits are replaced with the track momentum

**dual-readout is used here to correct energy of clustered calorimeter hits and improve track-hit matching*

Step 3) Jet clustering

- The jet clustering algorithm* is fed with the collection of
  - All photon hits (from step 1)
  - A collection of tracks
    - charged particles not reaching the calorimeter
    - tracks that were swapped with calorimeter hits at step 2
  - All the other calorimeter hits (both ECAL and HCAL) that have not been swapped out
- The algorithm clusters the 4 momentum vectors into two jets
- The jet energy ("non-swapped hadron" component) is corrected with DRO**

$$E_{jet} = C_{PFA} \cdot \left[\sum E_{hits,\gamma} + \sum E_{tracks} + \sum E_{hits,leftover,DRO} \right]$$

**FASTJET package:* generalized k_T algorithm with R=2π and p=1 (*ee_genkt_algorithm*), force number of jets to 2

***dual-readout is used here to correct energy of calorimeter hits which have not been matched to tracks (e.g. neutral hadrons)*